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Innovative Technologies and Techniques for *In-Situ* Test and Evaluation of Small Caliber Munitions

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The Georgia Tech Research Institute and the Army Research Laboratory have collaborated in the Defense Advanced Research Projects Agency–sponsored SCORPION program exploring the application of microadaptive flow control techniques to small caliber munitions. This article discusses innovative techniques and technologies created in pursuit of the development, test, and evaluation of this new control technology. Tools developed include the use of g-hardened sensors, processing and actuator control electronics in 25 mm and 40 mm munitions. Inertial measurement units meeting all survival, packaging, and power requirements were designed and implemented using low-cost commercial off-the-shelf sensors including micro-electromechanical systems accelerometers and rate sensors and solid state magnetometers. Using resources integrated on the processor, flight data were recorded and stored for post-flight retrieval. An innovative projectile soft capture system allowed the projectiles to be safely recovered and reused multiple times. Data analysis techniques were extended to evaluate the in-flight performance of the microadaptive flow control technology. Further, the data served as a diagnostic tool to compare system flight performance with ground-based tests.

Key words: dynamic engagement test environment; guidance and control; integrated electronics; Maneuverable munitions; microadaptive flow control technology; SCORPION Program; spinning projectiles.

The Future Force Concept for the U.S. Army clearly outlines a strategy for operational scenarios that feature combined-arms operations in a multi-threat, dynamic engagement environment. Precision small to medium caliber munitions are integral and necessary elements of this strategy. To meet this vision, innovative techniques and technologies are needed for both the realization and test and evaluation of small, spinning, guided projectiles.

With support and direction from the Defense Advanced Research Projects Agency (DARPA), the Georgia Institute of Technology and the U.S. Army Research Laboratory (ARL) have teamed on the SCORPION (Self CORrecting Projectile for Infantry OperatioN) program to explore and develop the applicability of Microadaptive Flow Control (MAFC) technology for aerodynamic steering of spinning projectiles.

The SCORPION program was a multi-phase effort that comprised an initial technology feasibility phase, a technology demonstration phase, and a follow-on extension. The objectives of the feasibility and demonstration phases were accomplished through the successful integration of MAFC into a 40 mm infantry grenade surrogate, while providing sufficient divert control authority and adequate guidance and control to correct for projectile delivery errors and achieve required target impact accuracies. The work in the follow-on phase explored advanced microgenerator actuator technology and application of adequate MAFC-based divert capability in a high subsonic velocity 25 mm projectile (McMichael 2004). Program objectives included

- Develop g-hardened gas generator actuators and fabrication technology;

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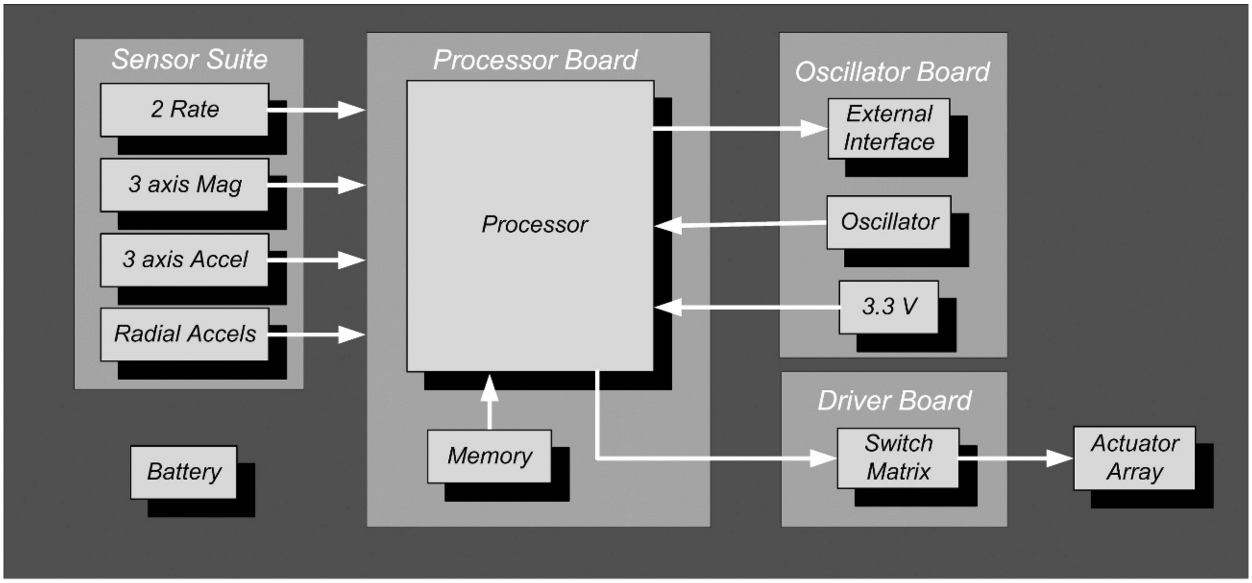

Figure 1. System block diagram showing sensor suite, processing, oscillator, and driver board

- Design, build, integrate, and test power, processor, and driver electronics for gas generator actuator systems;
- Research the nonlinear aerodynamics associated with the application of MAFC gas-generator actuators to high subsonic spinning projectiles;
- Integrate actuators and electronics into the flight control system;
- Miniaturize and g-harden the driver and flight control system for launch in a surrogate 25 mm projectile;
- Perform an open loop divert validation flight experiment of a gas generator actuator system using 40 mm projectile at Mach 0.25; and
- Perform an open loop divert validation flight experiment of a gas generator system using a 25 mm projectile at Mach 0.6 to 0.8.

This article summarizes the latest work concerning the open loop divert flight experiment of the high subsonic 25 mm projectile.

Integrated system description

While the program focus was on the development of MAFC technology, significant progress was made in the tools, techniques, and integration of technology for the guidance and control of small-caliber projectiles. Using a combination of commercial off-the-shelf components and components originally developed within the Hardened Subminiature Sensors Systems program for use in ARL's diagnostic fuze, an on-board inertial measurement system was designed and assembled (Lyons 2004).

The block diagram, *Figure 1*, shows the integrated electronics on board the 25 mm projectile. These electronics are hardened to withstand the in-bore acceleration forces experienced during gun launch.

Inertial sensor suite

The sensor suite contains two axes of rate sensors, three axes of accelerometers, and three axes of magnetometers oriented parallel to SCORPION's principal axes, and two additional radially oriented accelerometers. Outputs from these sensors combined with timing information from the oscillator were used by the processor to initiate commanded maneuvers. Sensor outputs were also stored in the processor for post-flight analysis and diagnostics. The processor and oscillator boards are shown in *Figure 2*. In *Figure 3*, the oscillator board, processor board, and the board-mounted sensor suite are combined (bottom to top) in a stack that functionally includes all the components of the inertial sensor suite (ISS) and the command guidance.

With the addition of batteries and a driver board, the electronics assembly is complete. This assembly along with the 25 mm SCORPION main body is shown in *Figure 4* with the driver board, batteries, inertial sensor

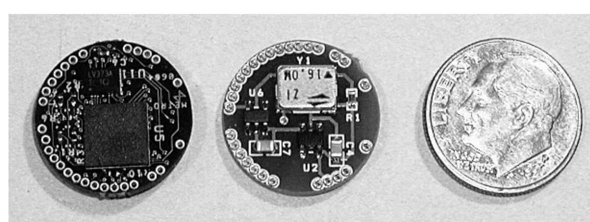

Figure 2. 25 mm SCORPION processor board and oscillator board

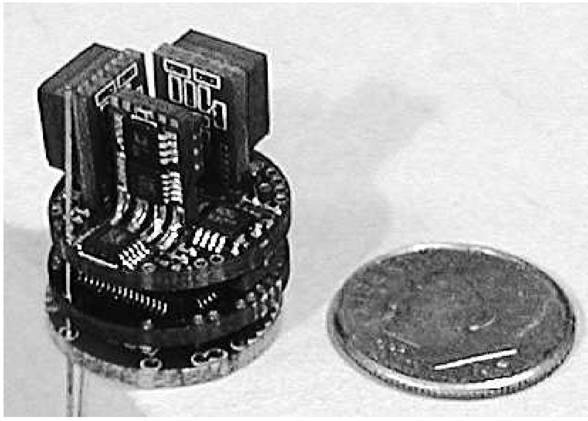

Figure 3. 25 mm SCORPION inertial sensor suite

boards, processor board, and oscillator/daughter board used for interface connection (from left to right, respectively). The diameter of each board is 17.5 mm, and the volume of the electronics package is 0.79 cu in.

On-board processing

Prior to launch, the on-board electronics are functionally checked and programmed with the initial flight conditions. The processor senses launch using the longitudinal accelerometer and starts the flight timing and data recording. The radial magnetometer is used to measure roll position and rate. For the open loop divert tests, the processor controls the start of the actuator firing sequence, the timing between firings, and the orientation of firing.

Calibration of inertial sensors was performed at various stages during the assembly process. However, careful attention to measuring the scale factor and bias was made before final assembly. Sensors were individually tested and aligned to assure that performance met requirements for bias and scale factor before integration with the electronics assembly. By using a methodical procedure of assembly and test from the component to the board level to the unit level, the need for corrective rework was reduced in the final assembly. Checkout and calibration of the integrated electronics included spin, magnetic, rate, and acceleration performance tests. Data from calibration performed after final assembly and potting were used to convert the inertial sensor outputs to engineering units.

Data acquisition system

An on-board data recording capability was developed and integrated into the SCORPION design. The data recorder stored 8064 records of data at programmable sampling rates from 1 kHz to 6 kHz. In typical conditions, the 4 kHz sample rate was used giving full coverage over the duration of flight lasting one to two seconds. The data system recorded 11 analog channels and four additional vehicle state channels. The data record had a 256 sample prelaunch record with the balance of recording data during flight.

Projectile design

The design of the 25 mm SCORPION was established with safety, reliability, and functionality in mind. The projectile is composed of two sections: the electronic control module and the actuator module. To meet the functional and safety criteria, the actuator module was separated from the rest of the assembly. This design allows for the separation of any potentially hazardous material, such as propellant, from the control electronics until just prior to firing. The electronics module is a potted cylindrical section housing the power, driver, IMU, processor, and connector boards, and a removable ogive (wind-shield) allowing access to the connector for communication, programming, and down-loading of data. The propul-

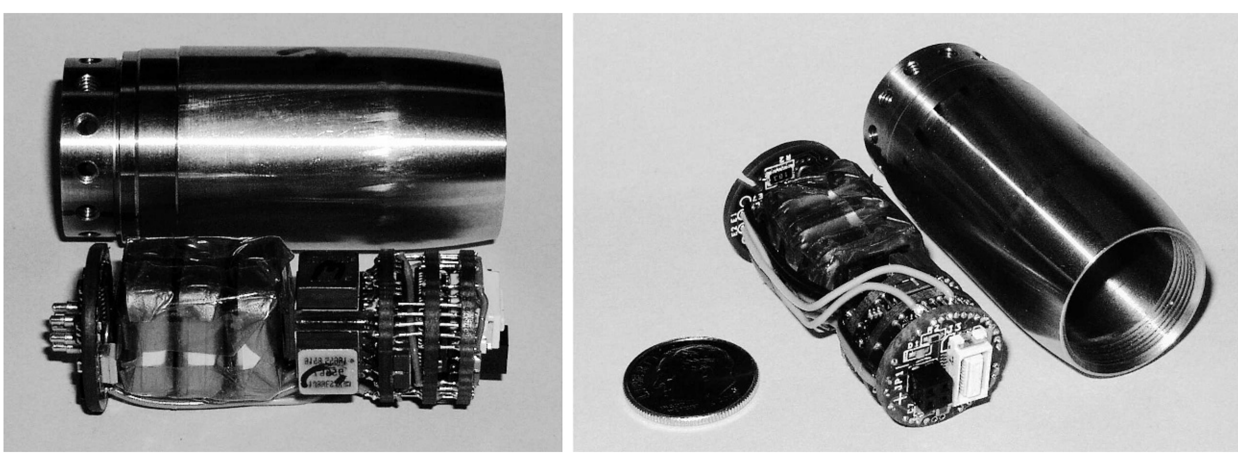

Figure 4. 25 mm SCORPION hardware and electronics assembly

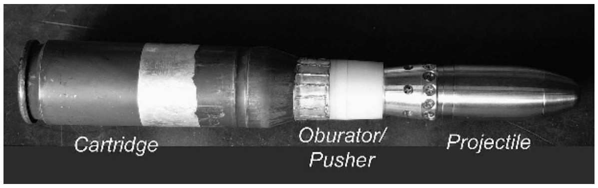

Figure 5. 25 mm SCORPION assembly with cartridge case, obturator/pusher, and projectile

sion system consists of a cartridge case housing the propellant, and an obturator/pusher assembly to seal the high pressure combustion gases in bore while transmitting torque for spin stabilization and distributing axial force to accelerate the projectile within the gun tube as shown in *Figure 5*.

Flight experiments

Initial flight experiments were conducted at ARL using a 25-mm barrel, shown in *Figure 6*, for interior ballistic design and soft recovery design. The primary objective for these tests was to establish an understanding of the propellant and cartridge case design required to launch the projectile at 0.8 Mach. This phase of experimentation was very successful at establishing a charge weight needed to meet the velocity requirements. Another goal was to establish a method of soft recovery for the 25-mm projectile. None of the techniques used in the past to recover small caliber projectiles was suitable for these tests because of the large standoff distances and other safety concerns. However, the idea of using layers of draped Kevlar to nondestructively absorb the kinetic energy of the bullet was explored and tested. This capture method proved successful as both the

Figure 6. 25-mm barrel used for interior ballistic design and obturator efficiency evaluation

Figure 7. Recovered projectile after successful in-flight silicon chip bridge initiation

projectile and the pusher were slowed and captured. One of the captured projectiles, shown in *Figure 7*, was recovered after sustaining a launch acceleration of 25,000 g's.

Spark shadowgraphs taken during a test flight trajectory are shown in *Figure 8*. The initial yaw of the projectile at launch is approximately two to three degrees. Yet, after the maneuver, the resulting angle of attack is approximately 17.5 degrees. This result closely matches predictions from modeled trajectory simulations of approximately 18 degrees computed before flight testing.

Data from two of the sensor channels recorded onboard the projectile during a representative flight experiment are shown in *Figure 9*. These data begin just prior to launch and continue until shortly after impact. Thus, data from the launch event and the entire free flight motion of the projectile before, during, and after maneuver are included. The commanded divert was a single initiation at a timed delay from the launch. The launch was internally detected through comparison to an on-board accelerometer. Depicted are the two of the three axes of magnetic field measurement. Also recorded are angular rate in both the pitch and yaw directions, accelerations in all three orthogonal directions, and outputs from an additional pair of accelerometers used to estimate the projectile spin rate. From this raw data, post-processing could be accomplished.

Post-flight processing

Formulations of projectile flight dynamics; guidance, navigation, and control; and strap-down sensor locations, orientations, and outputs are most often done in a so-called "projectile-fixed" or "body-fixed" coordinate system. This system is right-handed Cartesian

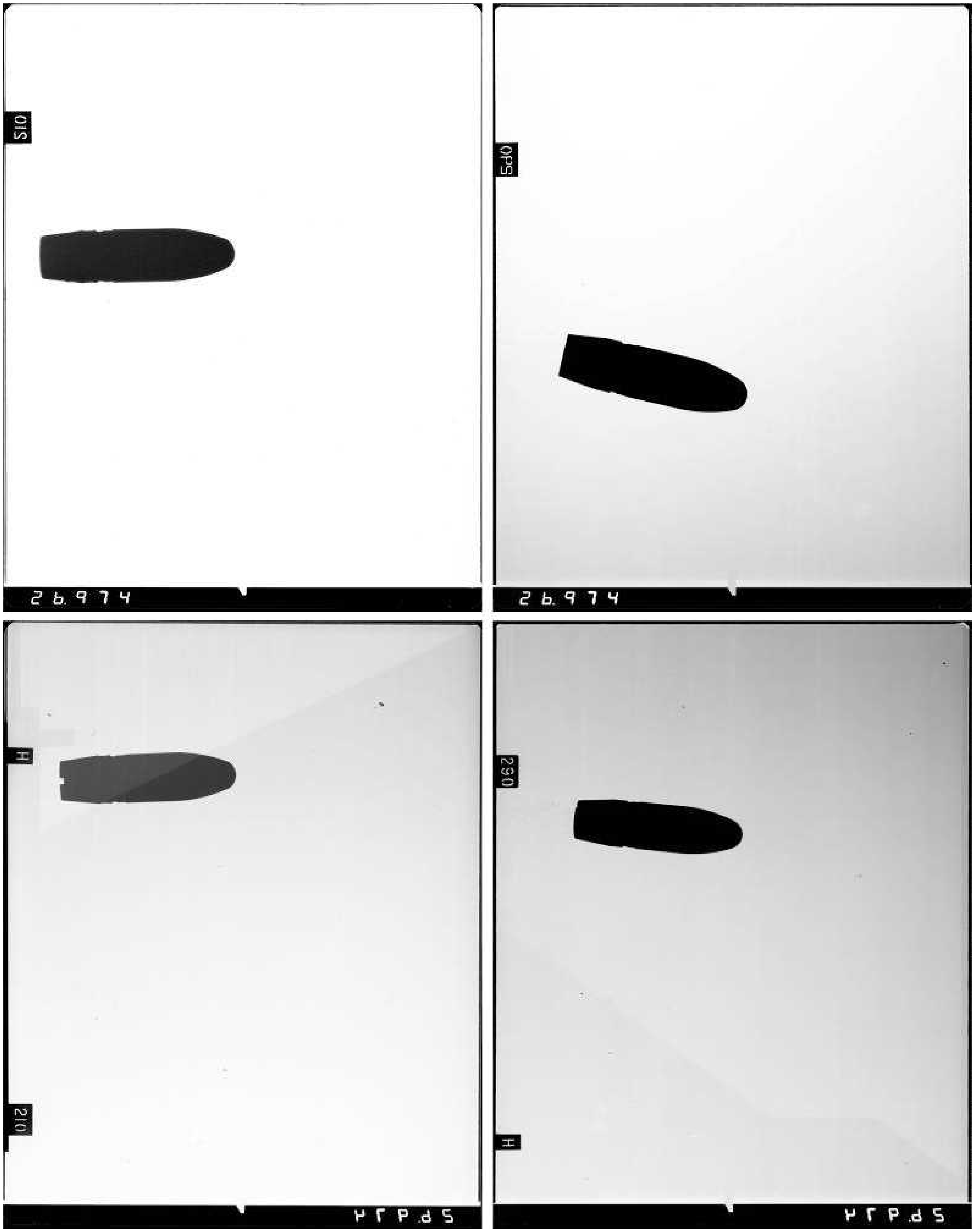

Figure 8. Orthogonal spark shadowgraphs depicting angle of attack before and after maneuver

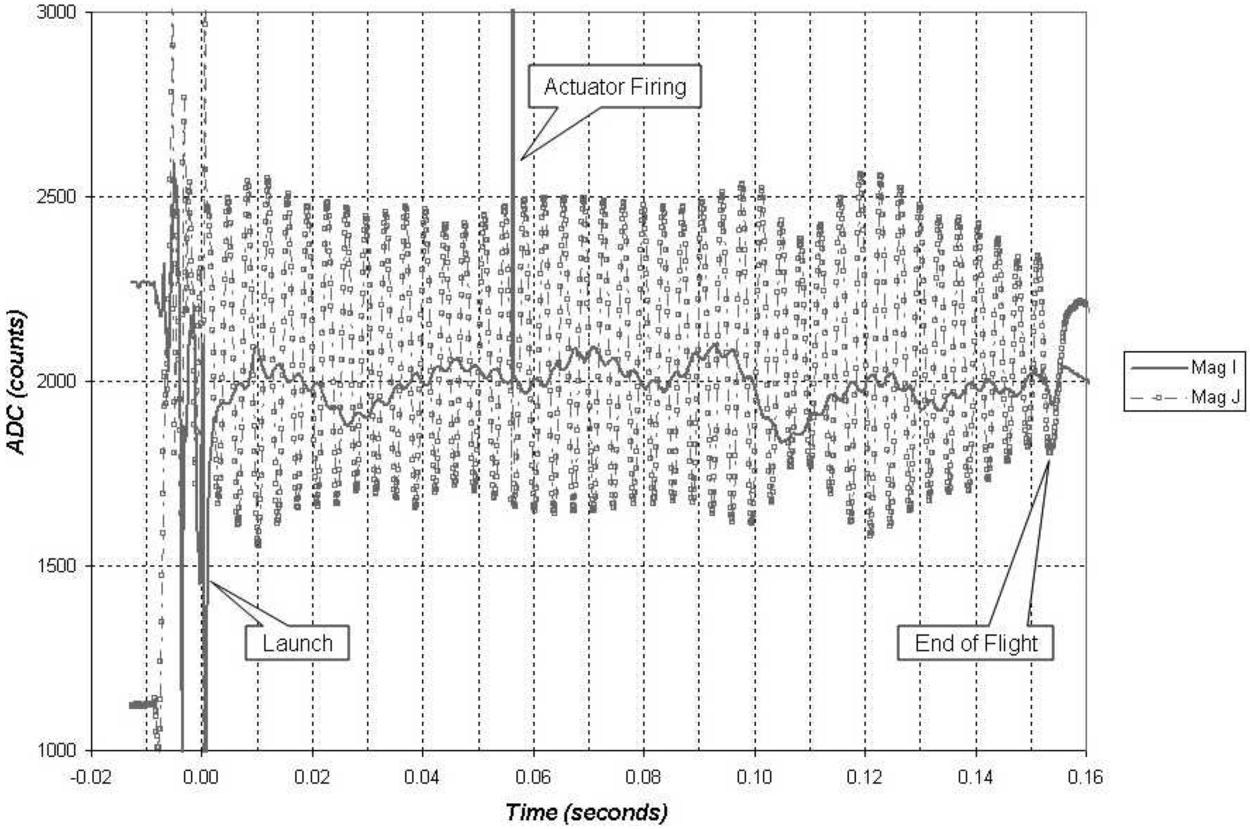

Figure 9. Recorded flight history of actuator initiation at approximately 0.06 seconds

with its origin at the center of gravity (cg) of the flight body. The body-fixed (I,J,K) coordinate system has its I axis lying along the projectile axis of symmetry, i.e., the spin axis (with positive in the direction of travel at launch). The J and K axes are then oriented so as to complete the right-handed orthogonal system *(Figure 10)*.

Among the many varieties of magnetic sensors, "vector" magnetometers are devices whose outputs are proportional to the magnetic field strength along the sensor's axis(es). SCORPION is equipped with a tri-axial vector magnetometer oriented with the sensor axes parallel to the projectile's principal axes. The

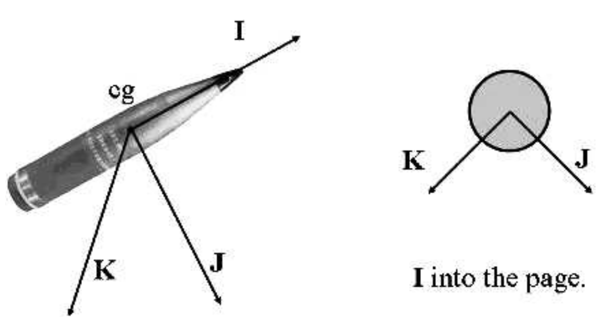

Figure 10. Body-fixed coordinate system

projections of the earth's magnetic field onto each of the sensor axes are given by the following equations:

$$M_I = \cos(\theta)\cos(\psi)M_n + \cos(\theta)\sin(\psi)M_e - \sin(\theta)M_v \tag{1}$$

$$\begin{aligned} M_J = {} & [\sin(\theta)\sin(\phi)\cos(\psi) - \cos(\phi)\sin(\psi)]M_n \\ & + [\sin(\theta)\sin(\phi)\sin(\psi) + \cos(\phi)\cos(\psi)]M_e \\ & + \cos(\theta)\sin(\phi)M_v \end{aligned} \tag{2}$$

$$\begin{aligned} M_K = {} & [\sin(\theta)\cos(\phi)\cos(\psi) + \sin(\phi)\sin(\psi)]M_n \\ & + [\sin(\theta)\cos(\phi)\sin(\psi) - \sin(\phi)\cos(\psi)]M_e \\ & = \cos(\theta)\cos(\phi)M_v \end{aligned} \tag{3}$$

where $\overrightarrow{M}_N = (M_N, M_e, M_v)$ is the magnetic field vector in a north, east, down earth–fixed navigation system, and (θ,ψ,ϕ) is the Eulerian projectile orientation vector in elevation, azimuth, and roll, respectively.

Because SCORPION's spin rate is large with respect to the yawing rates, the output from a magnetometer axis oriented parallel to the K body axis, designated Mag_K, is a sinusoid whose frequency varies with the projectile spin rate. For spin-stabilized and rolling

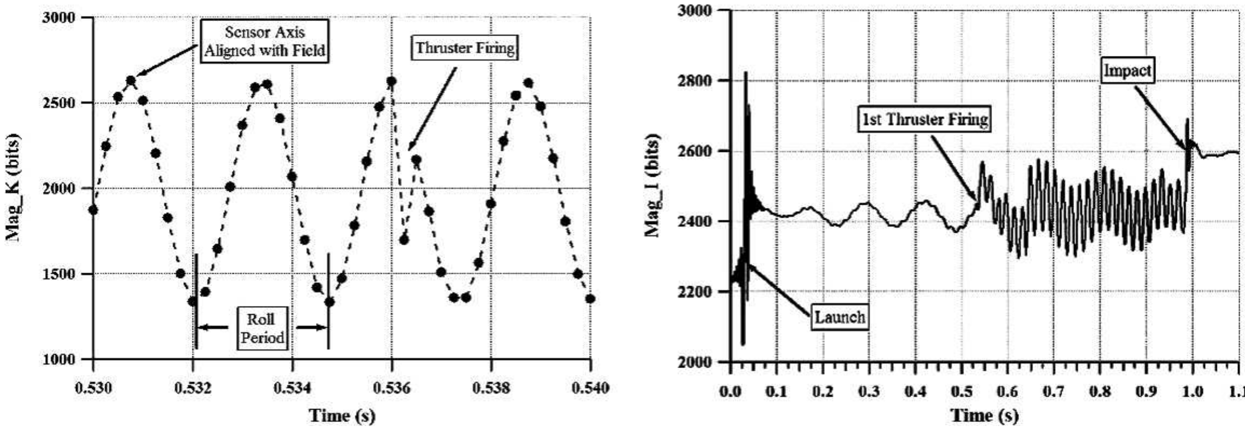

Figure 11. Representative magnetometer outputs: (left panel) radial magnetometer data—Mag_K, (right panel) axial magnetometer data—Mag_I

projectiles, the roll orientation must be known in order to properly execute desired maneuvers. With knowledge of the magnetic field, and knowledge of projectile elevation (θ) and azimuth (ψ), the roll angles at which Mag_K crosses the field (ϕ_M) correspond to the Mag_K extrema within a period. Ergo:

$$\phi_M = \tan^{-1}\left(\frac{\sin(\psi)M_n - \cos(\psi)M_e}{\sin(\theta)\cos(\psi)M_n + \sin(\theta)\sin(\psi)M_e + \cos(\theta)M_v}\right) \quad (4)$$

Evaluating Equation 3 at the principal value solution for ϕ_M shows whether Mag_K is at a maximum or minimum. Projectile roll orientation (ϕ) is estimated by computing ϕ_M at the times of each local maximum and minimum and then interpolating at intermediate times. Having thus produced a projectile roll angle history, the roll orientations at times of interest during flight can be computed. The output from an axis oriented parallel to the I body axis, Mag_I, varies directly with the angle between the spin axis and $\overrightarrow{M}_N$. This is called the magnetic aspect angle (σ_M). Time histories of σ_M provide information on projectile stability, yawing motion, damping characteristics, and maneuverability. An example of magnetometer data from a SCORPION experiment, annotated to highlight identifiable events during flight, is shown in *Figure 11*.

Post-flight application of these techniques to the magnetometer data yields critical information on maneuver mechanism performance and airframe response (see *Figure 11*). For this experiment, a 25 mm SCORPION projectile was programmed to execute a three-thruster divert to the right when looking downrange. After establishing the roll orientation of the Mag_K axis

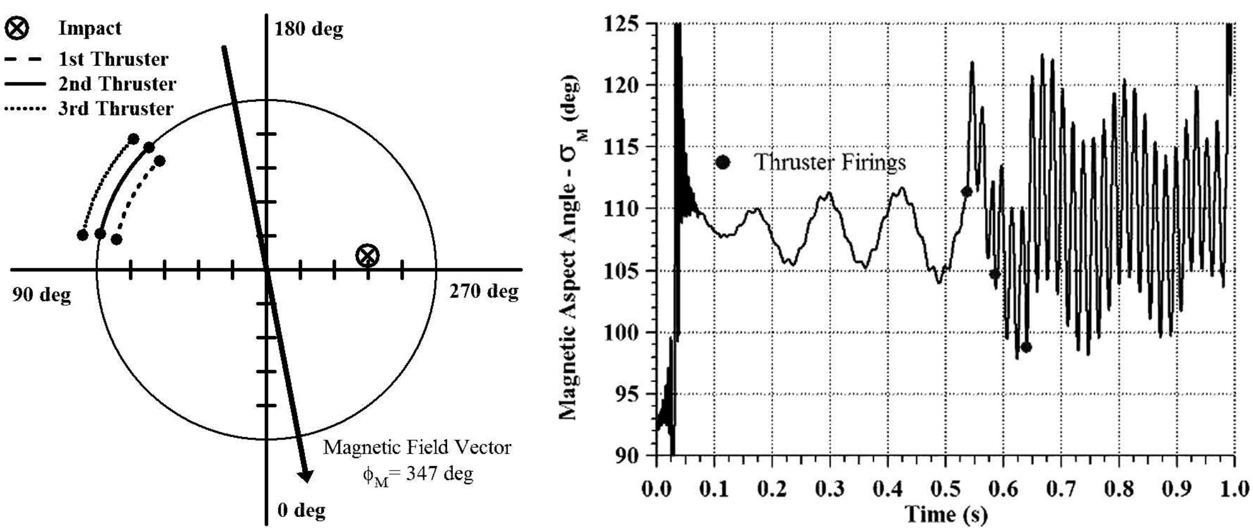

Figure 12. Performance measures derived from magnetometer data: (left panel) thruster orientations and projectile impact, (right panel) magnetic aspect angle history

at the thruster firing times, the roll orientation of the thruster nozzle when firing was computed from the known relative orientations of the thruster nozzles and magnetometer axes. The thruster orientations at their respective firing times are seen in *Figure 12 left panel* to be at about the 10 o'clock position. These orientations are plotted as arc segments to indicate the resolution of these roll angle measurements resulting from the combination of projectile spin rates and magnetometer sampling rates. These arcs indicate the performance of the on-board guidance, navigation, and control in executing the commanded maneuver. Also included in the figure is the projectile impact location (to the right) with respect to the mean impact point without maneuver. The associated magnetic aspect angle history, *Figure 12 right panel*, demonstrates that the yawing motion and maneuver, resulting from an individual thruster firing, depend on both the thruster orientation and the projectile yawing rates at the time of thruster firing. Understanding these interactions is crucial to designing an effective SCORPION guidance law in a tactical round.

Conclusions

In researching the feasibility of small caliber maneuvering munitions, a new diagnostic capability was developed. An integrated system design was required to provide a 17.5 mm data recorder with inertial sensor suite. This system has proven to survive in excess 25,000 g's in other applications. Its capability provides numerous opportunities for furthering the effort of guided small and medium caliber munitions. ❑

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